INTELLIGENT POWER QUALITY IMPROVEMENT IN HYBRID RENEWABLE ENERGY SYSTEMS VIA STATCOM AND GREY WOLF OPTIMIZATION

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ABSTRACT

This study presents an intelligent control approach to enhance power quality in a grid-connected hybrid renewable energy system integrating solar photovoltaic and wind sources. Such systems are highly susceptible to environmental variations, particularly wind speed fluctuations, which can reduce operational efficiency and stability. In addition, disturbances including three-phase faults and voltage deviations at the point of common coupling (PCC) may negatively influence system performance and reliability. To overcome these challenges, a Static Synchronous Compensator (STATCOM) is employed to provide dynamic reactive power support, thereby strengthening renewable energy integration and improving voltage regulation. Owing to the nonlinear and complex characteristics of hybrid systems, an advanced multi-objective Grey Wolf Optimization (GWO) algorithm is adopted to optimally tune controller parameters, enhancing robustness and overall system reliability. Simulation analyses under diverse operating conditions demonstrate that the system maintains voltage and current levels close to 1 pu during swell and sag events, ensures effective reactive power compensation during high renewable penetration, improves power quality under unbalanced nonlinear load conditions, and sustains PCC voltage within the range of 0.93–0.98 pu during three-phase faults. The results confirm notable improvements in voltage profile, current waveform quality, and Total Harmonic Distortion (THD), along with faster dynamic response, thereby validating the effectiveness of the proposed GWO-based STATCOM control strategy for hybrid renewable energy applications.

Keywords: *Static Synchronous Compensator (STATCOM), Grey Wolf Optimization (GWO), Reactive Power Regulation, Voltage Stability, Power Quality (PQ), Hybrid Energy Resource Systems (HRES).*

1. INTRODUCTION

The rapid growth in global electricity consumption has accelerated the integration of renewable energy sources (RES) into modern power systems [1]. Among these technologies, wind energy conversion systems (WECS) and photovoltaic (PV) generation have experienced remarkable expansion due to their environmental benefits and technological advancements [1]. However, the intermittent and fluctuating characteristics of these resources introduce significant operational challenges, particularly in maintaining voltage stability and ensuring acceptable power quality within the grid. Hybrid energy resource systems (HRESs), incorporating combinations of fuel cells (FCs), wind turbines, photovoltaic arrays, and biomass units, are increasingly connected to conventional electrical networks [2]. Each renewable source—whether operating as an AC or DC system—possesses distinct electrical and dynamic properties that differentiate it from other generation technologies [3]. When wind and PV systems operate together in hybrid arrangements, sustaining sufficient reactive power during fault conditions becomes more complex. Voltage variations frequently arise at the point of common coupling (PCC), where the hybrid system interfaces with the utility grid, potentially affecting system stability, degrading power factor, and reducing overall power quality [4,5]. Inadequate mitigation of these disturbances may lead to the disconnection of RES units in accordance with regulatory requirements such as the IRENA grid code [6].

To supply the necessary reactive power support and strengthen grid performance during disturbances, flexible AC transmission system (FACTS) devices are widely deployed [7]. By enhancing reactive power control, these devices improve the interaction between renewable generators and the power network. FACTS controllers are generally classified into series, shunt, and combined configurations, each offering specific functional advantages [8]. Series devices, including dynamic voltage restorers (DVRs), regulate line impedance and enhance transmission capability. Shunt devices, such as static VAR compensators (SVCs) and static synchronous compensators (STATCOMs), provide dynamic reactive power injection or absorption to counteract voltage sags and swells [9]. Combined controllers like the Unified Power Flow Controller (UPFC) and Unified Power Quality Conditioner (UPQC) integrate both series and shunt compensation features for comprehensive power management [10]. Although proportional–integral (PI) controllers are widely implemented due to their structural simplicity, their effectiveness in hybrid renewable systems depends greatly on accurate parameter tuning. The nonlinear behavior, structural complexity, and uncertainties introduced by multiple power electronic converters necessitate advanced optimization strategies for controller design [11]. Consequently, modern metaheuristic algorithms such as genetic algorithms (GA), particle swarm optimization (PSO), and grey wolf optimization (GWO) have been employed for optimal parameter adjustment, demonstrating superior performance compared to conventional tuning approaches [12].

The incorporation of renewable energy sources (RESs) into electrical grids has become indispensable for satisfying rising energy requirements while addressing environmental concerns [13,14]. Hybrid energy systems that integrate wind and photovoltaic generation offer a practical solution for meeting these demands in a sustainable manner [15]. Despite their advantages, such systems face operational challenges, including wind speed variability and grid faults that may lead to the disconnection of renewable units, thereby emphasizing the necessity for robust and adaptive control mechanisms. In this context, the Static Synchronous Compensator (STATCOM) plays a crucial role in strengthening voltage regulation and enhancing overall stability in hybrid configurations. This section reviews existing literature on STATCOM deployment, optimization-based tuning of PI controllers, and the contribution of Flexible AC Transmission Systems (FACTS) devices toward improving energy storage integration and grid performance. The study conducted by O. Ibitoye investigates the technical complexities associated with integrating RES into power distribution networks, particularly highlighting issues related to intermittency and uncertainty [16–18]. The work underscores the importance of advanced management and control strategies to maintain system stability and reliability in distribution systems with high renewable penetration. Similarly, Sinsel et al. point out that the inherent variability of renewable generation can cause significant mismatches between power supply and demand [19]. Their findings stress the importance of accurate forecasting methods to alleviate such imbalances, although existing approaches continue to face limitations due to persistent uncertainties in renewable generation patterns.

2. ARCHITECTURE AND OPERATIONAL FRAMEWORK OF THE PROPOSED HYBRID ENERGY RESOURCE SYSTEM (HRES)

Conventional generation units alone are no longer sufficient to satisfy the rapidly increasing power demand in modern electrical networks, leading to concerns regarding system reliability and protection coordination [20]. Hybrid Renewable Energy Source (HRES) systems have emerged as an advanced alternative, offering improved operational performance and enhanced supply reliability. However, when integrated with the utility grid, HRES installations introduce power quality (PQ) challenges that must be effectively mitigated to ensure dependable and flexible system operation [21]. Disturbances such as voltage sag, voltage swell, harmonics, and transient interference commonly arise due to renewable intermittency and grid interactions. To address these issues, a Static Synchronous Compensator (STATCOM) is incorporated into the HRES configuration in this work [22].

The STATCOM provides dynamic compensation by regulating both reactive and real power, thereby stabilizing voltage and improving overall PQ performance. The presence of nonlinear and unbalanced loads in grid-connected HRES further aggravates PQ disturbances, increasing harmonic content and voltage deviations. Identification and classification of these disturbances are carried out in accordance with established international standards, as organizations such as IEC and IEEE define comprehensive PQ guidelines to ensure uniformity and compliance in power systems [23], [24] as summarized in Table 1.

Table I. IEEE Standards Related to Power Quality Compliance and Regulation

Technical	Period	Amplitude
Hitches		
Dip	0.5–30 cycles	0.1–0.9 pu
Swell	0.5–30 cycles	1.1–1.9 pu
Fluctuation	Discontinuous	0.1–0.9 %
Under Voltage	> 60 s	0.8–0.9 pu
Over Voltage	> 60 s	1.1–1.2 pu
Interruption	0.5 cycle–30 s	< 0.1 pu
Noise	Steady-state	0–1 %
DC Offset	Steady-state	0–0.1 %
Harmonics	Steady-state	0–20 %

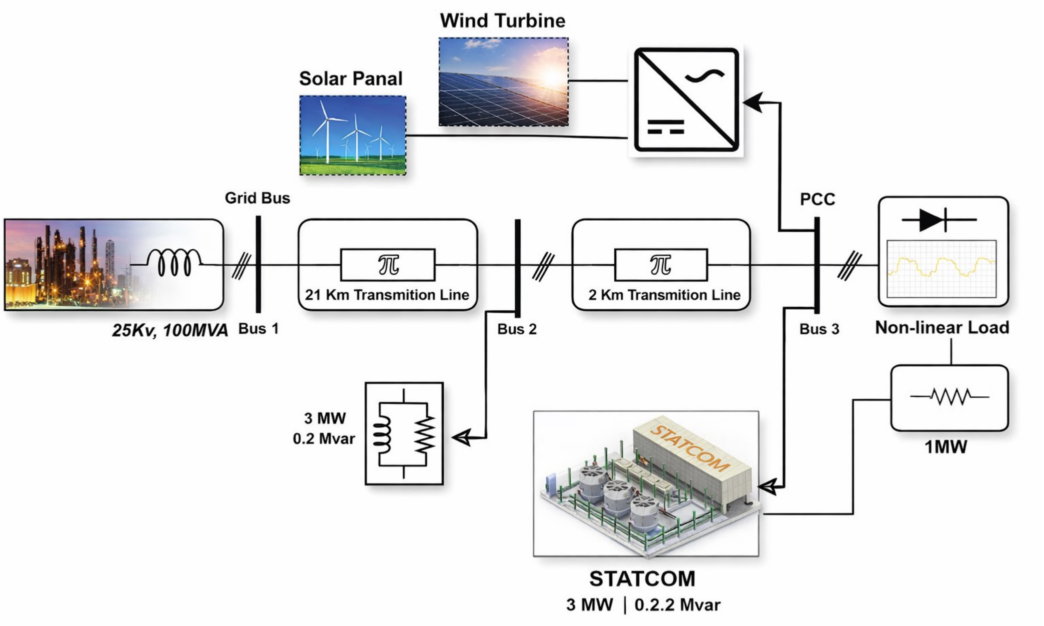

Figure 1. Structural Configuration of the Investigated Power System

The proposed configuration connects the wind turbine system and variable load to the utility grid through a power transformer, with a STATCOM integrated at the point of common coupling, as depicted in Figure 1. A Permanent Magnet Synchronous Generator (PMSG) is adopted in the wind energy conversion system due to its superior efficiency, reduced maintenance requirements, and improved dynamic performance compared to conventional generator types. This section details the mathematical modelling of both the wind turbine and photovoltaic subsystems to facilitate comprehensive analysis of the hybrid renewable energy system under study. When the HRES is interfaced with the synchronous grid (SG), operational challenges such as voltage variations and harmonic distortion arise, and these power quality concerns are examined and validated in the subsequent analysis.

This study evaluates the influence of a STATCOM on the performance of a Hybrid Renewable Energy System (HRES), considering climatic variations—particularly changes in wind speed—as external disturbances affecting system stability. For variable-speed wind energy applications, the Permanent Magnet Synchronous Generator (PMSG) is selected due to its high efficiency, compact design, and superior dynamic characteristics. In the proposed configuration, the wind turbine and generator are rated at 80 kW, with a base wind speed of 12 m/s, a rated mechanical speed of 3000 rpm, and 26 pole pairs. The schematic representation of the wind energy conversion system (WECS) is presented in Figure 2.

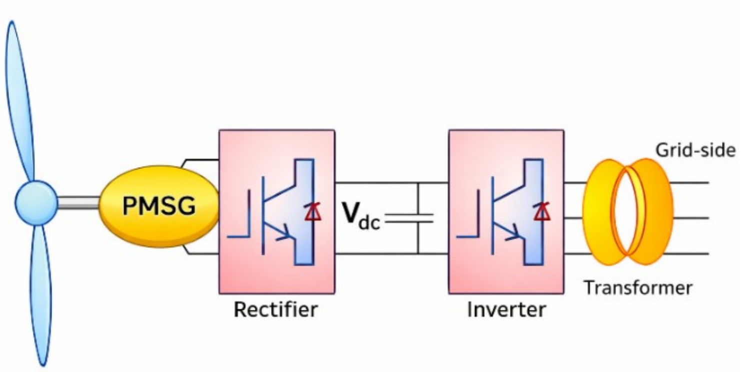

Figure 2. General Configuration of the Wind Turbine–PMSG System

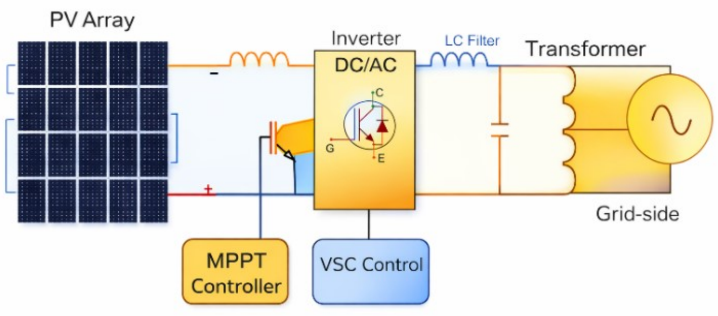

Figure 3. Structural Layout of the Grid-Connected Solar Photovoltaic

Over the past two decades, solar-based electricity generation has expanded considerably due to continuous improvements in photovoltaic cell efficiency and the declining cost of PV installations. The electrical output of a photovoltaic module is directly influenced by solar irradiance and ambient temperature, which determine the generated current and terminal voltage. In this work, the output power, current, and voltage of the designed PV array are analytically evaluated. Figure 3 presents the schematic configuration of the grid-connected solar PV system integrated with a Maximum Power Point Tracking (MPPT) controller.

The API-P250 module, rated at 250 Wp with a maximum power voltage (Vmpp) of 31.2 V and a maximum power current (Impp) of 8.03 A, is employed in the proposed model. The MPPT scheme is implemented using the Perturb-and-Observe (P&O) algorithm to ensure efficient tracking of the optimal operating point. However, variations in environmental conditions and load demand may prevent continuous operation at the true maximum power point. Therefore, coordinated MPPT control along with Voltage Source Converter (VSC) regulation is utilized to maximize energy extraction and ensure stable integration within the hybrid renewable energy system (HRES).

3. MODELING AND CONTROL FRAMEWORK OF THE PROPOSED STATCOM SYSTEM

Figures should be labeled with "Figure" and tables with "Table" and should be numbered sequentially, for example, Figure 1, Figure 2 and so on (refer to table 1 and figure 1). The figure numbers and titles should be placed below the figures, and the table numbers and titles should be placed on top of the tables. The title should be placed in the middle of the page between the left and right margins. Tables, illustrations and the corresponding text should be placed on the same page as far as possible if too large they can be placed in singly column format after text. Otherwise they may be placed on the immediate following page. If its size should be smaller than the type area they can be placed after references in singly column format and referenced in text

Enhancement of voltage profile and mitigation of power quality (PQ) disturbances in the network are achieved through the deployment of a Static Synchronous Compensator (STATCOM), which delivers rapid reactive power support at the point of common coupling (PCC). The implemented STATCOM configuration includes a 25 kV/1.25 kV coupling transformer, a voltage source converter (VSC) based on pulse-width modulation (PWM), LC-damped filters, a 10,000 µF DC-link capacitor, a voltage regulation unit, and anti-aliasing filters for accurate voltage and current measurement.

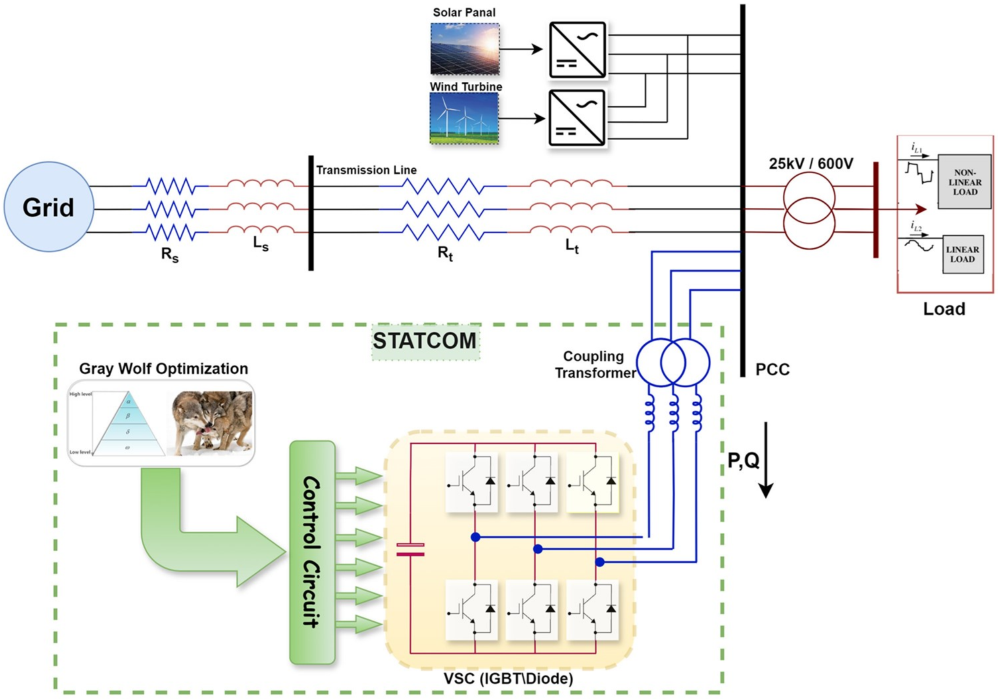

Figure 4. Architecture of the Proposed Hybrid System Integrated with STATCOM

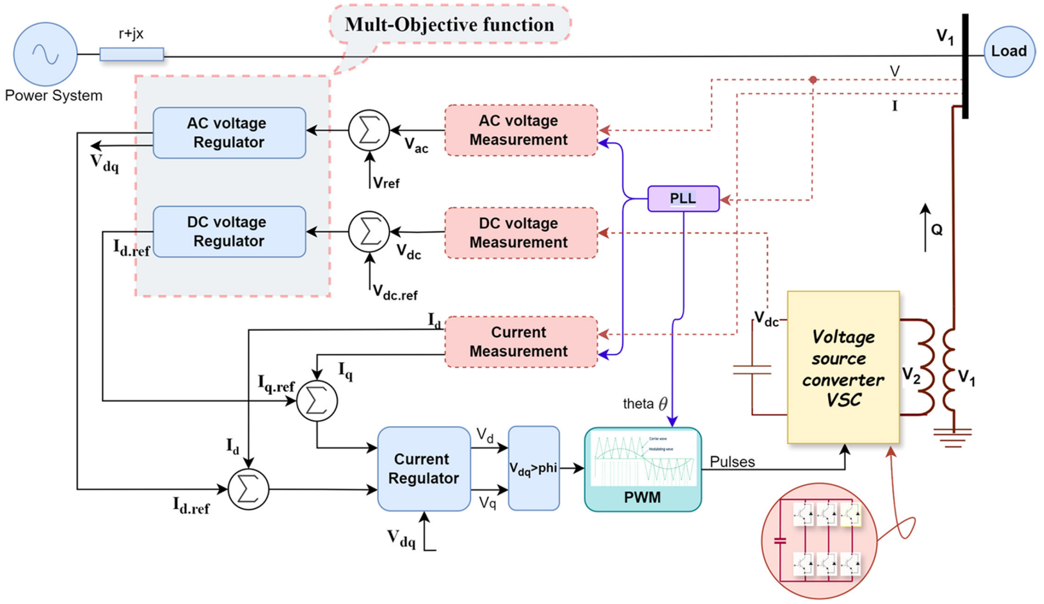

Figure 5. Block Diagram of the Proposed STATCOM Control System

Figure 4 presents the configuration of the power system integrated with the STATCOM. As a shunt-connected compensator, the STATCOM regulates active (P) and reactive (Q) power by dynamically injecting or absorbing reactive power through appropriate adjustment of the modulation index (m) and firing angle (α) within the PWM-controlled VSC. The converter processes and supplies the required compensation after filtering, while controller gain parameters are optimally tuned to ensure effective dynamic performance. In the proposed approach, a Grey Wolf Optimization (GWO)-based control algorithm is employed to compute the optimal controller settings, enabling efficient compensation under varying power quality conditions.

The STATCOM control scheme is generally structured with two primary control loops: an inner current regulation loop and an outer DC-link voltage control loop. The inner loop is responsible for controlling the AC-side currents to ensure accurate reactive power compensation, while the outer loop maintains the stability of the DC-link voltage. In addition, a Phase-Locked Loop (PLL) is employed to synchronize the converter with the grid voltage, and dedicated measurement units are used for precise acquisition of voltage and current signals. Figure 5 presents the overall single-line diagram of the STATCOM configuration together with a simplified block representation of the proposed control strategy, which is developed based on a multi-objective optimization framework.

4. PROPOSED OPTIMIZATION TECHNIQUE

The fundamental objective of multi-objective optimization algorithms is to obtain solutions that closely approximate the true global optimum while preserving adequate diversity among candidate solutions. In this study, the implementation begins with the formulation of the mathematical model governing STATCOM operation, including the voltage source converter representation, reactive power expression, and proportional–integral (PI) controller equations. Based on these relationships, a state-space model of the STATCOM is developed to describe its dynamic behavior.

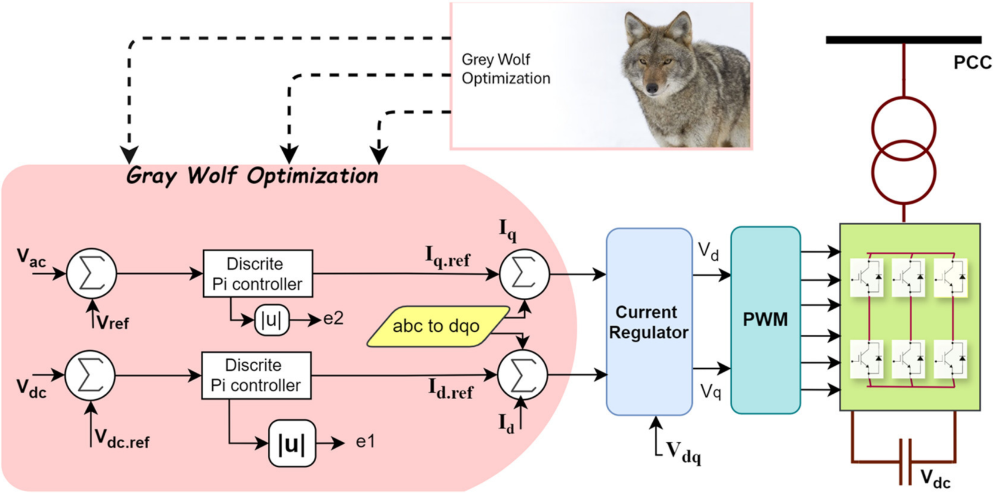

Figure 6. Structural Configuration of the GWO-Based STATCOM Controller

To address the resulting complex multi-objective optimization problem, a Grey Wolf Optimizer (GWO) is applied. The optimization framework simultaneously considers two key objectives, namely the tuning of the DC-link voltage controller and the AC voltage controller, as illustrated in Figure 6. Inspired by the social hierarchy and cooperative hunting strategy of grey wolves, the GWO algorithm effectively navigates the search space to achieve an optimal balance between these competing objectives, thereby enhancing overall control performance and system stability.

The proposed solution approach is structured to achieve efficient optimization while maintaining stable and reliable STATCOM operation. Ensuring robust dynamic performance is essential for effective reactive power compensation and voltage regulation. Accordingly, the optimization framework focuses on minimizing the Integral Time Absolute Error (ITAE), which quantifies the time-weighted absolute deviation between the reference signal and the actual system response. By reducing this performance index, the controller achieves improved transient behavior, enhanced accuracy, and greater reliability in STATCOM regulation under varying operating conditions.

4.1 Grey Wolf Optimizer (GWO) algorithm

Incorporating the Grey Wolf Optimizer (GWO) into STATCOM control systems offers significant practical advantages for modern power networks. Due to its effective balance between global exploration and local exploitation, GWO enables the controller to respond adaptively to dynamic operating conditions, thereby maintaining voltage stability and ensuring efficient reactive power compensation. Its rapid convergence characteristics allow the STATCOM to react promptly to system disturbances, minimizing response time and enhancing overall stability. Furthermore, the algorithm's simple structure and flexibility facilitate seamless integration into existing control architectures, making it a scalable and adaptable solution for diverse power system configurations.

Comparative studies have demonstrated that, when evaluated against other optimization techniques, GWO achieves superior performance in minimizing active power losses and improving bus voltage magnitude. Its strong capability in handling multi-objective problems, efficient search of complex solution spaces, balanced exploration–exploitation mechanism, and fast convergence behavior make it particularly suitable for tuning control parameters in renewable energy-based systems. These attributes position GWO as a robust and efficient optimization tool for enhancing STATCOM performance in hybrid renewable energy applications.

The optimization stage applies the Grey Wolf Optimizer (GWO) to determine the optimal proportional (Kp) and integral (Ki) gains of the PI controller. Initially, a population of candidate solutions, representing grey wolves, is randomly generated within predefined parameter limits. Each candidate is evaluated using a multi-objective fitness function that reflects the dynamic performance of the STATCOM-controlled hybrid power system. Based on the hierarchical leadership mechanism of alpha, beta, and delta wolves, the algorithm iteratively updates the positions of the search agents to guide the population toward improved solutions. Through successive iterations, the process converges to the optimal set of PI parameters that ensures enhanced voltage regulation, reactive power control, and overall system stability.

5. RESULTS ANALYSIS AND DISCUSSION

This section assesses the performance of the proposed optimization-based control strategy in mitigating power quality challenges within a grid-connected Hybrid Renewable Energy System (HRES). A detailed simulation model of the HRES integrated with a STATCOM is developed to verify the capability of the optimization approach in determining the optimal parameters of both DC-link and AC voltage regulators. By applying the optimized controller gains, the overall dynamic response of the system is significantly improved, particularly under abnormal operating conditions such as voltage sags and swells occurring at the point of common coupling (PCC).

Power quality evaluation is carried out using MATLAB for the optimization algorithm and the Simulink platform for dynamic system modeling. The analysis of power disturbances and their mitigation through advanced optimization techniques has become a prominent research focus in modern energy systems. In this study, system performance is examined under four distinct operating conditions, with key parameters including voltage, current, active power, and injected reactive power from the HRES–STATCOM configuration being monitored. The optimized controller parameters obtained through the proposed method are implemented in the system to validate performance improvements and ensure accuracy of results. The investigated conditions include voltage and current swell and sag events, high penetration of renewable energy sources, operation under unbalanced nonlinear load conditions, and the occurrence of a three-phase-to-ground fault. These test cases collectively demonstrate the robustness and effectiveness of the proposed optimization-based STATCOM control strategy in enhancing power quality and maintaining system stability. The STATCOM operates by dynamically injecting or absorbing reactive power to regulate the voltage at the point of common coupling (PCC). The voltage source converter (VSC) generates an output voltage synchronized in phase with the grid voltage. When the magnitude of the VSC output voltage is lower than the PCC voltage, the STATCOM behaves inductively and absorbs reactive power from the system. Conversely, when the VSC voltage magnitude exceeds the PCC voltage, the STATCOM operates capacitively, supplying reactive power to the grid to support voltage stability.

5.1 Case Study: Voltage and Current Swell and Sag Conditions

In this case, power quality disturbances cause voltage sag and swell conditions within the HRES. To maintain stable and linear system operation, these voltage and current variations must be effectively compensated. As shown in Figure 7, bus 1 experiences injected voltage disturbances in the form of sag and swell, while bus 3, representing the point of common coupling (PCC), exhibits the compensated voltage profile. The current $I_{STATCOM}$ (Ia) corresponds to the AC current injected by the STATCOM, illustrating the direction and timing of current flow from the voltage source converter (VSC) to the PCC. Through this injected current, the bus voltage is regulated and stabilized. In this operating condition, the STATCOM provides capacitive reactive power to counteract voltage sag, thereby restoring the PCC voltage to its desired level and improving overall power quality.

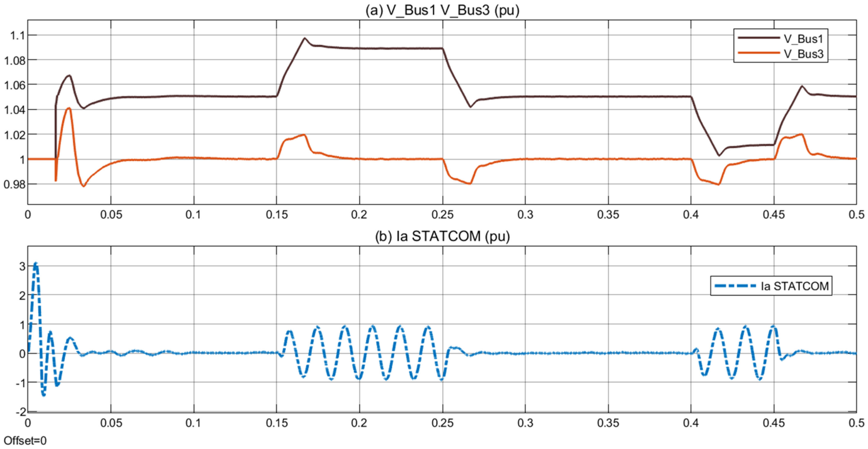

Figure 7. (a) Voltage Analysis at Bus 1 and Bus 3 (PCC); (b) Injected STATCOM Current (Ia).

5.2 Case Study: High Penetration of Renewable Energy Sources (RES)

The impact of varying renewable energy source (RES) penetration is examined to assess the capability of the STATCOM in regulating voltage disturbances at the point of common coupling (PCC). Under this operating condition, the proposed HRES supplies power directly to the PCC, and fluctuations in renewable generation introduce voltage variations due to their intermittent nature. One of the primary advantages of the STATCOM is its ability to enhance the voltage profile through dynamic reactive power compensation. By continuously adjusting reactive power exchange, the STATCOM mitigates voltage instability caused by rapid changes in renewable output, thereby facilitating smoother grid integration. To evaluate system performance, 60 kW of combined wind and solar power is injected into the network during the interval from 0.1 s to 0.35 s. This transient increase allows observation of the STATCOM's reactive power response. As illustrated in Figure 8, the STATCOM injects approximately −1.8 MVAr of reactive power, indicating operation in inductive mode to counterbalance the system conditions. The results confirm that the STATCOM effectively stabilizes PCC voltage during high renewable penetration, demonstrating its significant contribution to maintaining voltage stability and improving overall system performance under dynamically varying operating scenarios.

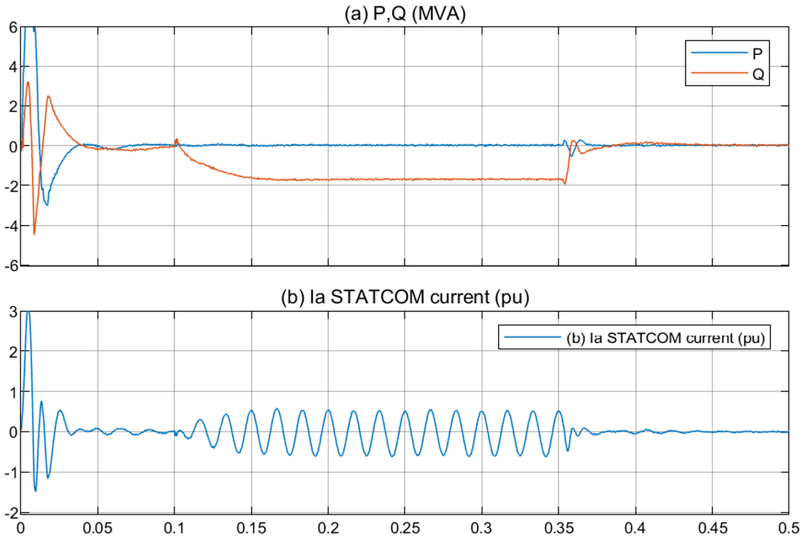

Figure 8. (a) Active and Reactive Power Response during RES Penetration (b) STATCOM Injected Current

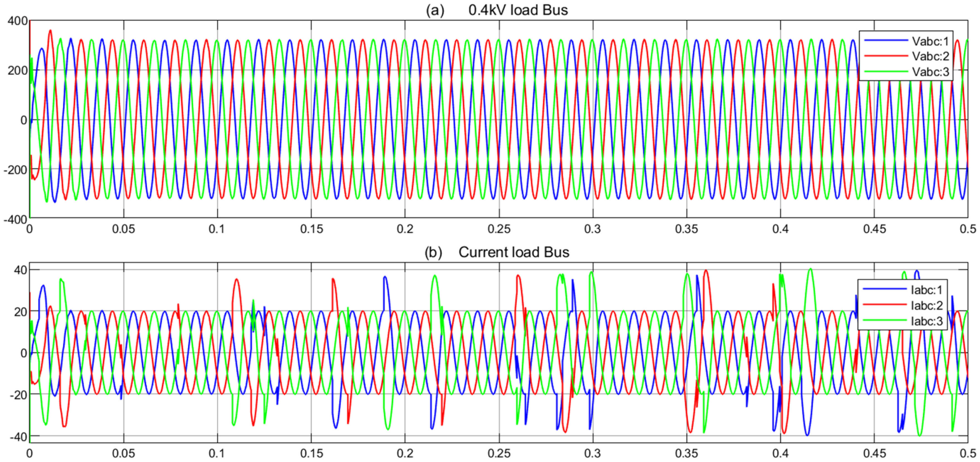

Figure 9. Load-Side Waveforms under Nonlinear Load: (a) Voltage and (b) Current

5.3 Case Study: Unbalanced Nonlinear Load Condition

To examine system performance under nonlinear loading conditions, a power electronic load with an R–L configuration is introduced. Nonlinear loads draw non-sinusoidal currents, generating harmonic components that are integer multiples of the fundamental frequency, thereby degrading power quality. Under this condition, significant harmonic distortion appears in the PCC voltage waveform.

With the implementation of the STATCOM, harmonic effects are effectively mitigated through dynamic current compensation. The Total Harmonic Distortion (THD) of the PCC voltage is reduced from 11.72% to 2.87%, representing an 8.85% improvement after compensation. Figures 9(a) and 9(b) illustrate the dynamic behavior of the load current and the voltage at the load terminal, demonstrating enhanced waveform quality and stability. Overall, the integration of the STATCOM in systems supplying nonlinear loads improves reactive power support, stabilizes voltage, and significantly enhances overall power quality.

5.4 Case Study: Three-Phase-to-Ground Fault Condition

To further verify the effectiveness of the proposed configuration, the system performance is evaluated under a three-phase-to-ground fault condition. In this case, a fault is introduced between 0.2 s and 0.36 s, a disturbance known to significantly affect voltage stability at the point of common coupling (PCC). Such severe symmetrical faults typically because substantial voltage drops and may threaten overall system stability if not properly mitigated.

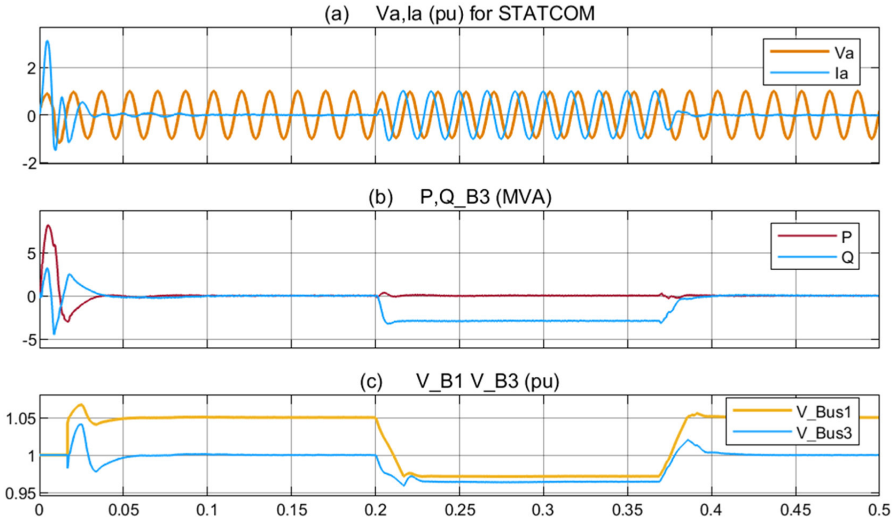

Figure 10. Three-Phase Fault Results: (a) STATCOM Current and Voltage (Ia, Va); (b) Active and Reactive Power at Bus 3; (c) Voltage Profiles at Bus 1 and Bus 3 (PCC)

The system is analyzed under faulted and compensated operating states to assess the dynamic response of the STATCOM. The results, illustrated in Figure 10, show that the PCC voltage is successfully maintained within the range of 0.92 to 0.97 pu during the fault interval. This demonstrates the STATCOM's capability to provide rapid reactive power support and stabilize the voltage profile under severe disturbance conditions. Consequently, the proposed control strategy ensures reliable fault ride-through performance and enhances the robustness of the hybrid renewable energy system against grid faults.

The performance of the proposed approach is benchmarked against results reported in existing studies employing various metaheuristic optimization techniques. Comparative evaluation of STATCOM-based control strategies indicates that the present work achieves superior voltage regulation performance, particularly in maintaining PCC voltage stability during fault conditions, where the voltage is effectively restored close to 0.97 pu through the application of the multi-objective Grey Wolf Optimization (GWO) method. Furthermore, harmonic analysis reveals significant reductions in Total Harmonic Distortion (THD), demonstrating the effectiveness of the proposed optimization strategy in improving waveform quality. Unlike many previous studies that focus on limited operating conditions, this work provides a comprehensive assessment across multiple disturbance scenarios, offering a more complete validation of STATCOM performance in hybrid renewable energy systems.

6. CONCLUSION

The incorporation of STATCOM technology within hybrid renewable energy systems (HRES) provides an effective approach for enhancing overall power quality. The intermittent nature of wind and photovoltaic generation introduces operational challenges during weather variations, grid faults, and nonlinear loading conditions. By applying a multi-objective optimization strategy based on the Grey Wolf Optimizer (GWO), the proposed framework improves voltage regulation at the point of common coupling (PCC) and optimizes reactive power exchange between the hybrid system and the STATCOM, thereby strengthening system stability and dynamic performance. The findings emphasize the significant contribution of the STATCOM in mitigating power quality disturbances such as voltage sags, swells, and harmonics arising from nonlinear loads and fault events. Simulation results demonstrate that HRES configurations equipped with STATCOM compensation exhibit markedly better performance compared to systems operating without such support. The proposed design enhances grid performance by reducing harmonic distortion, limiting voltage deviations, enabling efficient transfer of surplus renewable power to the grid, and maximizing renewable energy utilization. The developed modeling and optimization framework serves as a practical tool for the design and evaluation of STATCOM-based voltage and reactive power control strategies. Moreover, the comprehensive assessment across multiple operating scenarios validates the robustness of the improved optimization approach for hybrid renewable integration. Validation through MATLAB/Simulink simulations confirms the effectiveness of the GWO algorithm in determining optimal STATCOM controller parameters. These results highlight the potential of the proposed optimization technique as a reliable and scalable solution for future advancements in power quality enhancement and renewable energy integration within modern power systems.

REFERENCES:

[1] A. Panda, A.K. Dauda, H. Chua, R.R. Tan, K.B. Aviso, Recent advances in the integration of renewable energy sources and storage facilities with hybrid power systems, Clean. Eng. Technol. 12 (2023) 100598, https://doi.org/10.1016/j. clet.2023.100598.

[2] G. Ali, H.N. Musbah, H.H. Aly, T. Little, Hybrid Renewable Energy Resources Selection Based on Multi Criteria Decision Methods for Optimal Performance, IEEE Access 11 (February 2023) (2023) 26773–26784, https://doi.org/10.1109/ ACCESS.2023.3254532.

[3] J. Jayaram, M. Srinivasan, N. Prabaharan, T. Senjyu, Design of Decentralized Hybrid Microgrid Integrating Multiple Renewable Energy Sources with Power Quality Improvement, Sustain 14 (13) (2022), https://doi.org/10.3390/ su14137777.

[4] A. Fatih Guven, A.Y. Abdelaziz, M.Mahmoud Samy, S. Barakat, Optimizing energy Dynamics: A comprehensive analysis of hybrid energy storage systems integrating battery banks and supercapacitors, Energy Convers. Manag. 312 (2024) 118560, https://doi.org/10.1016/j.enconman.2024.118560.

[5] A. El Ghaly, M. Tarnini, Z. Al Barakeh, K. Chahine, Compensating voltage waveform distortions using a practical topology of series

active power filters, Results Eng 22 (January) (2024) 102032, https://doi.org/10.1016/j.rineng.2024.102032.

[6] IRENA, Grid codes for renewable powered systems, 2022. Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Grid_Codes_Renewable_Systems_2022.pdf?rev=986f108cbe5e47b98d17fca93eee6c86.

[7] C.R. Reddy, B.S. Goud, F. Aymen, G.S. Rao, E.C. Bortoni, Power quality improvement in hres grid connected system with fopid based atom search optimization technique, Energies 14 (18) (2021), https://doi.org/10.3390/en14185812.

[8] O.D. Montoya, C.A. Ramírez-Vanegas, J.R. Gonz´alez-Granada, Dynamic active and reactive power compensation in distribution networks using PV-STATCOMs: A tutorial using the Julia software, Results Eng 21 (January) (2024) 101876, https://doi.org/10.1016/j.rineng.2024.101876.

[9] M.K. Abdullah, L.H. Hassan, M. Moghavvemi, Voltage stability assessment of grid connected PV systems with FACTS devices, Sci. Rep. 12 (1) (2022) 1–16, https://doi.org/10.1038/s41598-022-26751-5.

[10] B.H. Alajrash, M. Salem, M. Swadi, T. Senjyu, M. Kamarol, S. Motahhir, A comprehensive review of FACTS devices in modern power systems: Addressing power quality, optimal placement, and stability with renewable energy penetration, Energy Reports 11 (2024) 5350–5371, https://doi.org/10.1016/j.egyr.2024.05.011.

[11] B. N. Bhukya, P. R. Chinda, S. R. Rayapudi, and S. R. Bondalapati, “Congestion management of power transmission line with advanced interline power flow controller,” Journal of Mechatronics, Electrical Power, and Vehicular Technology, vol. 16, no. 1, pp. 52–68, Jul. 2025.

[12] M.M. Samy, R.E. Almamlook, H.I. Elkhouly, S. Barakat, Decision-making and optimal design of green energy system based on statistical methods and artificial neural network approaches, Sustain. Cities Soc. 84 (2022) 104015, https://doi.org/10.1016/j.scs.2022.104015.

[13] S. R. Bondalapati, B. N. Bhukya, G. V. P. Anjaneyulu, M. Ravindra, and B. S. Chandra, “Bidirectional power flow between solar-integrated grid to vehicle, vehicle to grid, and vehicle to home,” Journal of Applied Science and Engineering, vol. 27, no. 5, pp. 2571–2581, 2024.

[14] H.-G. Vu and D. N. Huu, “Evaluation of the Impact of Rooftop Solar Power on the Power Quality of Vietnam Urban Distribution Networks according to Relevant Vietnamese and IEEE and IEC Standards”, Eng. Technol. Appl. Sci. Res., vol. 14, no. 3, pp. 14685–14691, Jun. 2024.

[15] A. Aljaberi, M.F. Alwaeli, M. Al-Anbagi, Technical, Economic, and Environmental Analysis of Solar System with Management Considering Flexible Energy Sources in an Educational Building, in: BIO Web Conf 97, 2024, https://doi.org/10.1051/bioconf/20249700065.

[16] A.F. Güven, N. Y¨orükeren, M.M. Samy, Design optimization of a stand-alone green energy system of university campus based on Jaya-Harmony Search and Ant Colony Optimization algorithms approaches, Energy 253 (2022) 124089, https://doi.org/10.1016/j.energy.2022.124089.

[17] E. Bushra, K. Zeb, I. Ahmad, M. Khalid, A comprehensive review on recent trends and future prospects of PWM techniques for harmonic suppression in renewable energies based power converters, Results Eng 22 (August 2023) (2024) 102213, https://doi.org/10.1016/j.rineng.2024.102213.

[18] R. Adware and V. Chandrakar, “A Hybrid STATCOM Approach to Enhance the Grid Power Quality associated with a Wind Farm”, Eng. Technol. Appl. Sci. Res., vol. 13, no. 4, pp. 11426–11431, Aug. 2023.

[19] M. Bilal, P.N. Bokoro, G. Sharma, Hybrid optimization for sustainable design and sizing of standalone microgrids integrating renewable energy, diesel generators, and battery storage with environmental considerations, Results Eng 25 (December 2024) (2025) 103764, https://doi.org/10.1016/j.rineng.2024.103764.

[20] Z. Chen, A.M. Amani, X. Yu, M. Jalili, Control and Optimisation of Power Grids Using Smart Meter Data: A Review, Sensors 23 (4) (2023), https://doi.org/10.3390/s23042118.

[21] B.S. Goud, B.L. Rao, Power Quality Enhancement in Grid-Connected PV/Wind/Battery Using UPQC: Atom Search Optimization, J. Electr. Eng. Technol. 16 (2)

(2021) 821–835, https://doi.org/10.1007/s42835-020-00644-x.

[22] M. Kandasamy, et al., Strategic incorporation of DSTATCOM and distributed generations in balanced and unbalanced radial power distribution networks considering time varying loads, Energy Reports 9 (2023) 4345–4359, https://doi. org/10.1016/j.egyr.2023.03.076.

[23] J.D. Combita-Murcia, C.A. Romero-Salcedo, O.D. Montoya, D.A. Giral-Ramírez, Dynamic compensation of active and reactive power in distribution systems through PV-STATCOM and metaheuristic optimization, Results Eng 22 (May) (2024) 102195, https://doi.org/10.1016/j.rineng.2024.102195.

[24] N. Shabbir, L. Kütt, M. Jarkovoi, M.N. Iqbal, A. Rass˜olkin, K. Daniel, An overview of measurement standards for power quality, Agron. Res. 19 (1) (2021) 944–960, https://doi.org/10.15159/AR.21.074. Special Issue.